Whole-Heart Coronary MRA

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Background

MRI was first reported to visualize the ostia of the coronary arteries in the late 1980's (1, 2). Tremendous progress has been made in coronary MRA ever since. One of the milestones was the acquisition of k-space data in a segmented mode (3, 4), allowing collection of an entire data set within multiple heartbeats. Early coronary MRA studies used two-dimensional (2D) technique to acquire single-slice images within a single breath hold (4-6). Three-dimensional (3D) acquisition has now become the major method of choice not only because of its higher signal-to-noise ratio (SNR) than 2D methods, more importantly, the acquisition of contiguous thin slices improves the delineation of torturous coronary arteries and facilitates post-processing of images (7-9).

The development of navigator-echo methods a decade ago provides a way to monitor the diaphragm motion in real-time. Respiratory motion of the heart was correlated to that of the diaphragm with a correction factor for respiratory gating (10-12). Imaging time can be extended from previous one breath-hold to several minutes with free breathing. Higher spatial resolution and/or slab coverage can be achieved as a result. A recent multicenter study of 109 patients using navigator-echo gating method showed the sensitivity, specificity, and accuracy for patients with disease of the left main coronary artery or three-vessel disease to be 100%, 85%, and 87%, respectively (13). In these studies, a volume-targeted scan was usually prescribed to cover each of the major coronary arteries.

Due to the intrinsically tortuous course and the epicardial situation of major coronary arteries, it has always been of interest to scan the whole heart to depict the entire coronary artery tree. An early study collected multiple overlapped 3D slabs to cover the whole heart using retrospective respiratory gating (14). Long segments of all three major coronary arteries were reported. Thick slab coverage (40 slices with 2 mm thickness) was also achieved within a single breath-hold by using a segmented echo-planar imaging (EPI) method. An extravascular contrast agent was administered to boost the blood signal and imaging contrast (15). However, EPI techniques suffer from low SNR and spatial resolution. Recently, blood-pool contrast agents have been developed to allow whole-heart coverage of navigator-echo guided coronary MRA using conventional gradient-echo sequence (16). However, these agents have not yet been approved for clinical applications.

With the recent improvement in gradient systems, steady-state free precession (SSFP) imaging techniques have been extensively used in cardiac MRI (17, 18). The increased SNR of SSFP over conventional gradient-echo sequences makes it feasible to image with higher spatial resolution or imaging speed. Recent developments in parallel imaging techniques accelerated data acquisition by reconstructing images from undersampled data sets (19, 20). With advanced design of data acquisition and image reconstruction schemes, parallel imaging techniques can be used to improve the spatial resolution and/or reduce the imaging time without inducing imaging artifacts.

Advances of these techniques make it possible to collect the full whole heart data set within a reasonable imaging time (around 10 minutes). A recent study performed whole-heart coronary MRA using a free-breathing SSFP sequence with magnetization preparation and parallel data acquisition (21). The results from 12 normal volunteers showed that the whole-heart coronary MRA technique significantly improved the visible vessel lengths as compared to conventional thin-slab methods. High-quality coronary artery images of the complete coronary artery tree were acquired in a single measurement with a $1\times1\times1.5$ mm^3 (reconstructed to $0.5\times0.5\times0.75$ mm^3) resolution. Some example whole-heart coronary MRA images are given in Fig. 1. In addition, no precise image plane planning was required as in volume-targeted imaging.

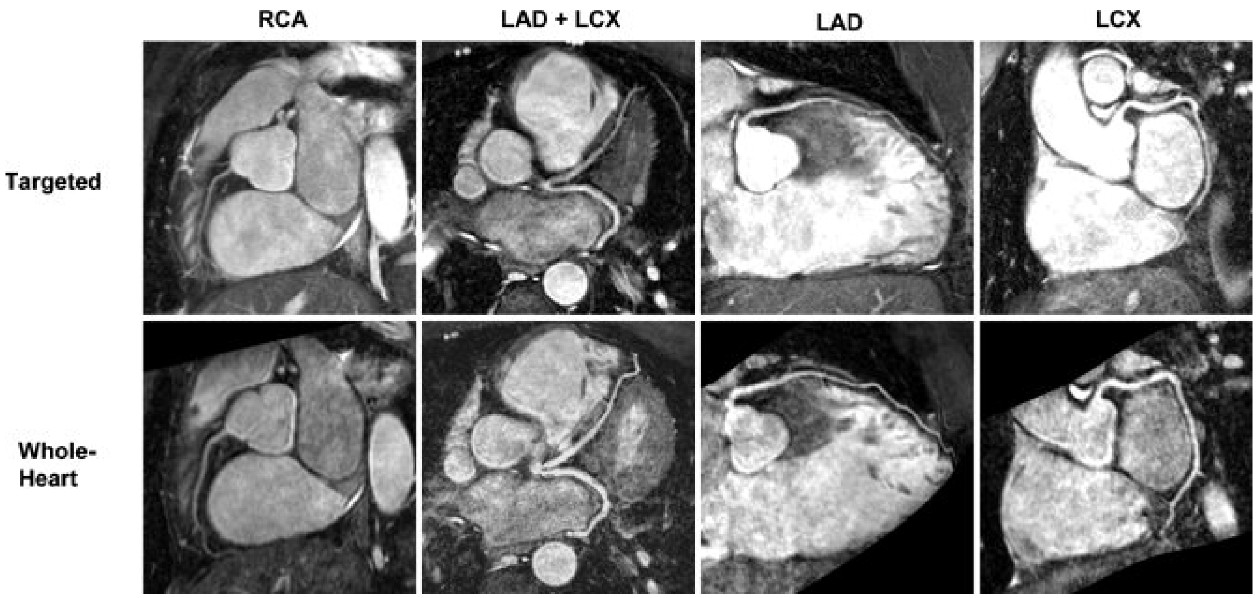
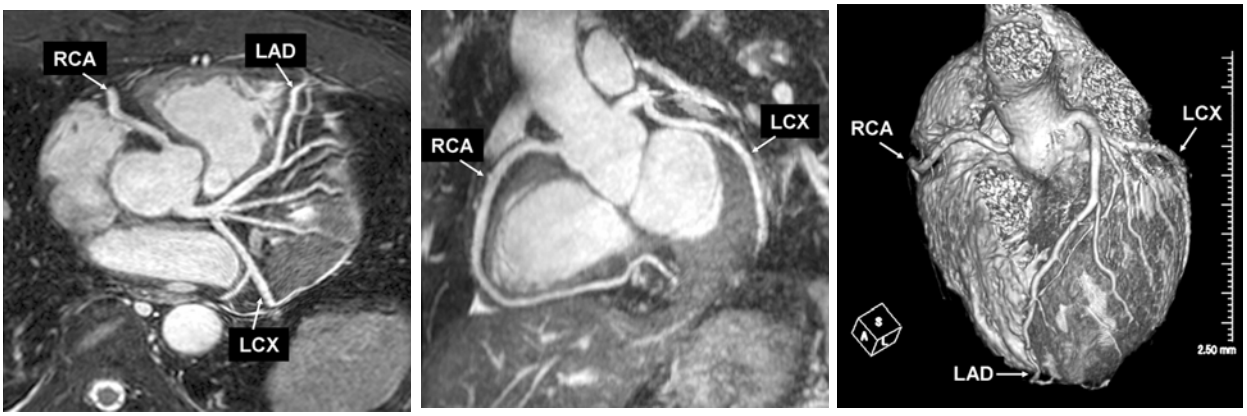


Figure 1. Coronary arteries of a volunteer. Note that contrast to the background is improved, especially in the more distal segments of the LAD and LCX. In the LAD+LCX visualization of the whole-heart approach, the length of the vessels is only partly shown, as vessels orthogonal to the visualization plane are poorly visualized in this type of reconstruction. This problem did not occur in the transverse-targeted volume, because the imaged volume did not cover the critical part of the vessels. Alternative orientations provided better visualization of the LAD and LCX in both approaches. (Reprinted from reference 21)

Whole-heart coronary MRA was also successfully performed in suspected patients of coronary artery disease in a recent study. SSFP sequence was used in that study with free breathing (22). The average imaging time was 13.8 ± 3.8 minutes. The sensitivity, specificity, accuracy, and positive and negative predictive values of whole-heart 3D coronary MR angiography in the detection of significant stenoses in the major coronary arteries were 82% (14 of 17 arteries), 91% (39 of 43 arteries), 88% (53 of 60 arteries), 78% (14 of 18 arteries), and 93% (39 of 42 arteries), respectively. Images of two patient studies are shown in Figs. 2 and 3.



(a) (b) (c)

Figure 2. Reformatted whole-heart coronary MR angiograms (4.6/2.3, navigator-gated 3D steady-state free precession sequence with fat saturation and T2-weighted preparation) in 42-year-old man with normal coronary arteries. **(a)** Left anterior oblique image reformatted with curved multiplanar reformation clearly depicts RCA and LCX artery. **(b)** Oblique transverse image reformatted with curved multiplanar reformation shows left main coronary artery, LAD artery, and proximal portions of the RCA and the LCX artery. **(c)** Left anterior oblique volume-rendered image is useful for general anatomic recognition of the LAD and LCX arteries. (Reprinted from reference 22)

(a) (b)

Figure 3. Coronary artery images obtained in 78-year-old man with significant stenoses in the RCA. **(a)** Conventional coronary angiogram in left anterior oblique view shows significant luminal stenoses (arrows) in the proximal and middle parts of the RCA and diffuse atherosclerotic changes (arrowheads). **(b)** Left anterior oblique whole-heart coronary MR angiogram (4.6/2.3, navigator-gated 3D steady-state free precession sequence with fat saturation and T2-weighted preparation) reformatted with curved multiplanar reformation shows significant luminal narrowing (arrows) in the proximal and middle parts of the RCA and diffuse atherosclerotic plaque (arrowheads). (Reprinted from reference 22)

Advantages of whole-heart MRA

The major advantage of performing whole-heart coronary MRA is that long segments of all major coronary arteries can be visualized. Overall imaging time can potentially be reduced as compared to conventional volume-targeted method. Although it took 13.8 minutes on average for one whole-heart scan in previous studies (21, 22), all major coronary arteries are depicted in a single measurement. The requirement of planning imaging orientation and running double-oblique scan for each coronary artery in conventional volume-targeted method is eliminated. Including the initial scout scans, the entire coronary MRA study can be completed in less than 30 minutes using the whole-heart approach (22).

Another advantage is that the scan procedure is much simplified using the whole-heart method. Conventional volume-targeted methods rely on the skill of the operator to determine the orientation of each single coronary artery. Using the whole-heart method, a scout scan covering three orthogonal orientations of the heart is usually adequate to define the transverse imaging plane. The imaging procedure is less user-dependent and variations of coronary artery delineations due to imaging plane selections can be substantially reduced.

Typical imaging protocols

A typical imaging protocol of performing whole-heart coronary MRA at 1.5T includes:

A survey scan in three orthogonal orientations (transverse, coronal, and sagittal orientations, three slices in each orientation) to localize the heart and the diaphragm, as well as to confirm the coil positioning;

A separate scan to investigate the sensitivity of coil elements if sensitivity encoding (SENSE) is used to accelerate the coronary MRA;

A high temporal resolution cine scan in the axial (22) or four-chamber (21) view to scout the motion of coronary arteries. Cardiac phases showing minimal motions (typically during mid-diastole) will be selected for data acquisition;

High-resolution coronary MRA using segmented SSFP sequence covers the whole heart in the transaxial orientation. Typically, T_2-preparation (23) is applied to increase the blood-myocardium contrast. Respiratory motion is compensated by real-time navigator gating which collects 1D data from a pencil beam placed on the dome of the right diaphragm.

Other parameters: 20 – 30 k-space lines per heartbeat, spectrally selective fat saturation, navigator gating window: 5 mm, spatial resolution ~ $1.0\times1.0\times1.5$ mm^3 which can be interpolated to $0.5\times0.5\times0.75$ mm^3. With a navigator gating efficiency of 40-50% and a SENSE factor of 2, the imaging time is typically 10-15 min.

Current limitations

Respiratory motion and cardiac motion continue to be the major challenge for coronary MRA. Imaging time for one whole-heart measurement is still long (10 – 15 minutes) at current stage even with parallel imaging factor of two. Drift of the diaphragm and fluctuations of the breathing pattern during this period can decrease the respiratory-gating efficiency, increase respiratory motion artifacts, or even lead to failure of the measurement. This was the major reason that 5 out of the 39 patient studies were not completed in the previous study (22).

Navigator-echo based respiratory gating method indirectly estimates the respiratory motion of the heart based on the motion of the diaphragm. Hysteretic effects such as weak correlation of relative displacements between the diaphragm and the heart can degrade the quality of respiratory gating and induce image blurring and artifacts.

Variations of the heart rate over long imaging time may compromise the optimal trigger delay time and the width of the data acquisition window determined from the precedent cine scan and lead to blurring of the coronary vessels.

Limited by imaging time and signal-to-noise, the spatial resolution of the coronary MRA is still low as compared to conventional X-ray angiography and CTA.

Ongoing research and future directions

The major focus of ongoing research in whole-heart coronary MRA is to reduce the imaging time and/or increase the spatial resolution without severely compromising the SNR and image quality. Continued developments in imaging hardware and pulse sequence design make it possible to further improve the whole-heart coronary MRA technique.

Increasing the number of receiver channels (e.g., 32-channel coil) has been shown to increase the SNR of cardiac images. In addition, increased coil elements can potentially be used for parallel imaging with higher acceleration factors (e.g., parallel acquisition in both phase-encoding and partition-encoding directions).

Previous studies had shown promising results in acquiring high-resolution, large volume coverage coronary artery images in a single breath-hold (15, 24). With further development of parallel imaging techniques and receiving coils, this can become a very promising technique for whole-heart coronary MRA with acceptable spatial resolution. Previously mentioned problems associated with the prolonged imaging time can potentially be eliminated.

4D (3D cine) acquisition has been implemented to acquire time-resolved coronary artery images (25, 26). The need of predetermining the trigger delay time and data acquisition window is removed by continuously acquiring 3D data throughout the cardiac phases. In addition, images at multiple cardiac phases with minimal motion can be averaged retrospectively to optimize the SNR without compromising the sharpness of coronary arteries. Extension of such a 4D technique to whole-heart imaging can preserve all these advantages. Furthermore, cine images can be reformatted from the whole-heart 4D data in desirable orientations for the evaluation of the cardiac wall motion.

T_1-shortening contrast agent can potentially be used to increase the blood-myocardium contrast in whole-heart coronary MRA. Currently, the major obstacle of using clinical available Gadolinium-based extravascular agents for whole-heart imaging is its weak ability of vascular containment. As a result, images have to be acquired during the first arterial pass of the contrast agent. The intravascular half-life of newly developed blood pool contrast agents is much longer. Relatively long imaging time can be used without significant drop of blood signal intensity. Recently, slow infusion of a high relaxivity clinical extravascular contrast agent (MultiHance, Bracco Imaging) (27) was also shown to enhance the coronary blood for several minutes, which can potentially be used for whole-heart coronary MRA.

Recently proposed cardiac and respiratory self-gated acquisition techniques removed the need for indirect gating of cardiac motion from ECG or indirect gating of respiratory motion from the diaphragm (28, 29). Motion synchronization signal was directly extracted from the same MR signals used for image reconstruction, providing precise motion of the heart. A recent study demonstrated the feasibility of using respiratory self-gating approach in conjunction with 3D radial acquisition for coronary MRA (30). Isotropic resolution of images reconstructed from 3D radial data also facilitates the reformatting of images.

In conclusion, whole-heart coronary MRA provides a way of imaging the entire coronary artery tree within one measurement. Long segments of all major coronary arteries can be visualized with whole-heart coverage of the scan. It is a promising technique for non-invasive imaging of coronary arteries.

References

1. Lieberman JM, Botti RE, Nelson AD. Magnetic resonance imaging of the heart. Radiol Clin North Am 1984; 22:847-858.
2. Paulin S, von Schulthess GK, Fossel E, Krayenbuehl HP. MR imaging of the aortic root and proximal coronary arteries. AJR Am J Roentgenol 1987; 148:665-670.
3. Burstein D. MR imaging of coronary artery flow in isolated and in vivo hearts. J Magn Reson Imaging 1991; 1:337-346.
4. Edelman RR, Manning WJ, Burstein D, Paulin S. Coronary arteries: breath-hold MR angiography. Radiology 1991; 181:641-643.
5. Meyer CH, Hu BS, Nishimura DG, Macovski A. Fast spiral coronary artery imaging. Magn Reson Med 1992; 28:202-213.
6. Manning WJ, Li W, Boyle NG, Edelman RR. Fat-suppressed breath-hold magnetic resonance coronary angiography. Circulation 1993; 87:94-104.
7. Li D, Paschal CB, Haacke EM, Adler LP. Coronary arteries: three-dimensional MR imaging with fat saturation and magnetization transfer contrast. Radiology 1993; 187:401-406.
8. Paschal CB, Haacke EM, Adler LP. Three-dimensional MR imaging of the coronary arteries: preliminary clinical experience. J Magn Reson Imaging 1993; 3:491-500.
9. Wang Y, Grimm RC, Rossman PJ, Debbins JP, Riederer SJ, Ehman RL. 3D coronary MR angiography in multiple breath-holds using a respiratory feedback monitor. Magn Reson Med 1995; 34:11-16.
10. Sachs TS, Meyer CH, Hu BS, Kohli J, Nishimura DG, Macovski A. Real-time motion detection in spiral MRI using navigators. Magn Reson Med 1994; 32:639-645.
11. Wang Y, Rossman PJ, Grimm RC, Riederer SJ, Ehman RL. Navigator-echo-based real-time respiratory gating and triggering for reduction of respiration effects in three-dimensional coronary MR angiography. Radiology 1996; 198:55-60.
12. Hofman MB, Paschal CB, Li D, Haacke EM, van Rossum AC, Sprenger M. MRI of coronary arteries: 2D breath-hold vs 3D respiratory-gated acquisition. J Comput Assist Tomogr 1995; 19:56-62.
13. Kim WY, Danias PG, Stuber M, et al. Coronary magnetic resonance angiography for the detection of coronary stenoses. N Engl J Med 2001; 345:1863-1869.
14. Li D, Kaushikkar S, Haacke EM, et al. Coronary arteries: three-dimensional MR imaging with retrospective respiratory gating. Radiology 1996; 201:857-863.
15. Deshpande VS, Wielopolski PA, Shea SM, Carr J, Zheng J, Li D. Coronary artery imaging using contrast-enhanced 3D segmented EPI. J Magn Reson Imaging 2001; 13:676-681.
16. Li D, Zheng J, Weinmann HJ. Contrast-enhanced MR imaging of coronary arteries: comparison of intra- and extravascular contrast agents in swine. Radiology 2001; 218:670-678.
17. Deshpande VS, Shea SM, Laub G, Simonetti OP, Finn JP, Li D. 3D magnetization-prepared true-FISP: a new technique for imaging coronary arteries. Magn Reson Med 2001; 46:494-502.

18. Scheffler K, Heid O, Hennig J. Magnetization preparation during the steady state: fat-saturated 3D TrueFISP. Magn Reson Med 2001; 45:1075-1080.
19. Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P. SENSE: sensitivity encoding for fast MRI. Magn Reson Med 1999; 42:952-962.
20. Griswold MA, Jakob PM, Heidemann RM, et al. Generalized autocalibrating partially parallel acquisitions (GRAPPA). Magn Reson Med 2002; 47:1202-1210.
21. Weber OM, Martin AJ, Higgins CB. Whole-heart steady-state free precession coronary artery magnetic resonance angiography. Magn Reson Med 2003; 50:1223-1228.
22. Sakuma H, Ichikawa Y, Suzawa N, et al. Assessment of coronary arteries with total study time of less than 30 minutes by using whole-heart coronary MR angiography. Radiology 2005; 237:316-321.
23. Brittain JH, Hu BS, Wright GA, Meyer CH, Macovski A, Nishimura DG. Coronary angiography with magnetization-prepared T2 contrast. Magn Reson Med 1995; 33:689-696.
24. Niendorf T, Sodickson DK, Hardy CJ, et al. Towards whole heart coverage in a single breath-hold: coronary artery imaging using a true 32-channel phased array MRI system. In: Proc. Intl. Soc. Mag. Reson. Med. Kyoto, Japan, 2004; 703.
25. Park J, Larson AC, Zhang Q, Simonetti O, Li D. 4D radial coronary artery imaging within a single breath-hold: cine angiography with phase-sensitive fat suppression (CAPS). Magn Reson Med 2005; 54:833-840.
26. Bi X, Park J, Larson AC, Zhang Q, Simonetti O, Li D. Contrast-enhanced 4D radial coronary artery imaging at 3.0 T within a single breath-hold. Magn Reson Med 2005; 54:470-475.
27. Knopp MV, Runge VM, Essig M, Hartman M, Jansen O, Kirchin MA, Moeller A, Seeberg AH, Lodemann KP. Primary and secondary brain tumors at MR imaging: bicentric intraindividual crossover comparison of gadobenate dimeglumine and gadopentetate dimeglumine. Radiology 2004; 230:55-64.
28. Larson AC, Kellman P, Arai A, et al. Preliminary investigation of respiratory self-gating for free-breathing segmented cine MRI. Magn Reson Med 2005; 53:159-168.
29. Larson AC, White RD, Laub G, McVeigh ER, Li D, Simonetti OP. Self-gated cardiac cine MRI. Magn Reson Med 2004; 51:93-102.
30. Stehning C, Bornert P, Nehrke K, Eggers H, Stuber M. Free-breathing whole-heart coronary MRA with 3D radial SSFP and self-navigated image reconstruction. Magn Reson Med 2005; 54:476-480.